# CP Violation in the B System: Searching for New Physics

David London

McGill University

and

Université de Montréal

May 13, 2004

# CP Violation in the Standard Model

In the SM, CP violation is due to a complex phase in the CKM matrix:

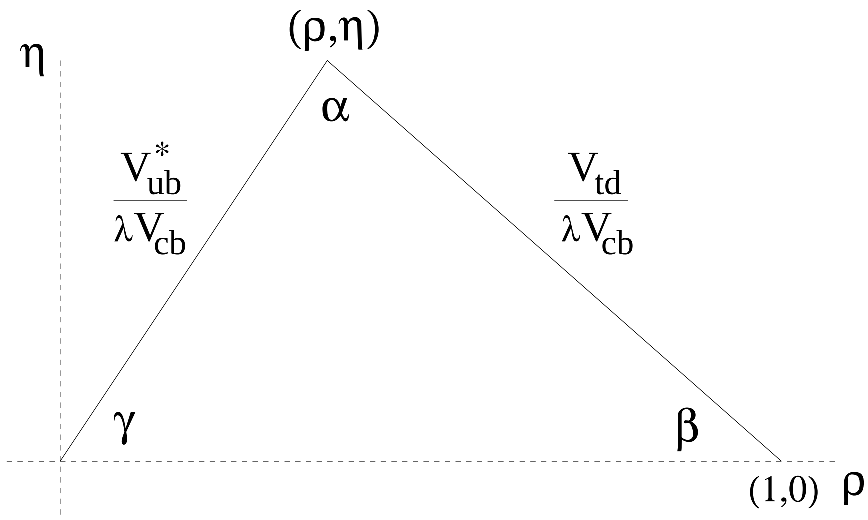
$$V_{CKM} \simeq \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3\left(\rho-i\eta\right) \\ -\lambda(1+iA^2\lambda^4\eta) & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3\left(1-\rho-i\eta\right) & -A\lambda^2 & 1 \end{pmatrix}$$

where $\lambda = 0.22$.

Note: (i) relative sizes of CKM matrix elements, (ii) large phases occur only in corners: $V_{ub}$ and $V_{td}$.

Unitarity Triangle:

$$V_{CKM} \simeq \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & |V_{ts}| & |V_{tb}| \end{pmatrix}$$



# CP Violation in the $B$ System

CP violation requires interference of 2 amplitudes. Consider the decay $B \to f$. Suppose

$$\begin{aligned} A(B \to f) &= A_1 e^{i\phi_1} e^{i\delta_1} + A_2 e^{i\phi_2} e^{i\delta_2} \ , \\ A(\bar{B} \to \bar{f}) &= A_1 e^{-i\phi_1} e^{i\delta_1} + A_2 e^{-i\phi_2} e^{i\delta_2} \ . \end{aligned}$$

Define **direct** CP asymmetry:

$$\mathcal{A}_f \equiv \frac{\Gamma(B \to f) - \Gamma(\bar{B} \to \bar{f})}{\Gamma(B \to f) + \Gamma(\bar{B} \to \bar{f})} = - \frac{2 A_1 A_2 \sin\Phi \sin\Delta}{A_1^2 + A_2^2 + 2 A_1 A_2 \cos\Phi \cos\Delta} \ ,$$

where $\Phi \equiv \phi_1 - \phi_2$ and $\Delta \equiv \delta_1 - \delta_2$.

Note: direct CP asymmetry depends on unknown strong phases. Cannot extract weak phase information ($\Phi$) without hadronic input.

There is another signal of CP violation. Use $B^0$–$\bar{B}^0$ mixing. Choose final state $f$ accessible to both $B^0$ and $\bar{B}^0$. (Simplest is CP eigenstate.) Then $B^0 \to f$ and $B^0 \to \bar{B}^0 \to f$ interfere. Get **indirect** CP asymmetry:

$$\Gamma(B^0(t) \to f) \sim B + a_{dir} \cos(\Delta M t) + a_{indir} \sin(\Delta M t)$$

with

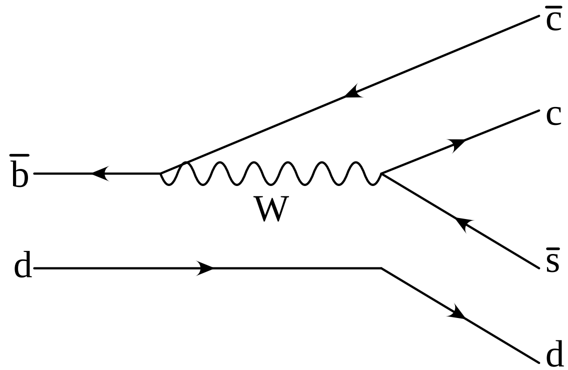
$$B \equiv \frac{1}{2}\left(|A|^2 + |\bar{A}|^2\right) \ , \ a_{dir} \equiv \frac{1}{2}\left(|A|^2 - |\bar{A}|^2\right) \ , \ a_{indir} \equiv \mathrm{Im}\left(e^{-2i\beta} A^* \bar{A}\right) \ .$$

Point: $\Gamma(B^0(t) \to f)$ gives 3 measurements.

Note: if there is only a single decay amplitude in $B^0 \to f$, i.e. $A_2 = 0$, then $a_{dir} = 0$, but $a_{indir} \neq 0$. This is the most interesting case, since all dependence on unknown strong phases vanishes.

Idea: measure $\alpha$, $\beta$, $\gamma$ in ways independent of strong phases.

$\beta$: $B_d^0(t) \rightarrow J/\psi K_S$. Decay dominated by tree $T' \sim V_{cb}^* V_{cs}$ (real).
Indirect CPV measures phase of $B_d^0$–$\bar{B}_d^0$ mixing: $2\,\arg(V_{tb}^* V_{td}) = -2\beta$.

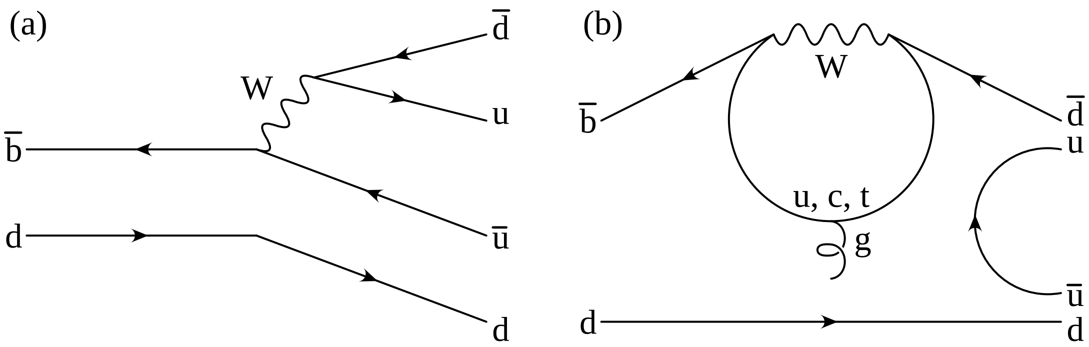



Both BaBar and Belle have measured this:

$$\sin 2\beta = 0.736 \pm 0.049 \ .$$

As we will see, this agrees with independent measurements.

$\alpha$: $B_d^0(t) \to \pi^+\pi^-$. Here the decay has two contributions:



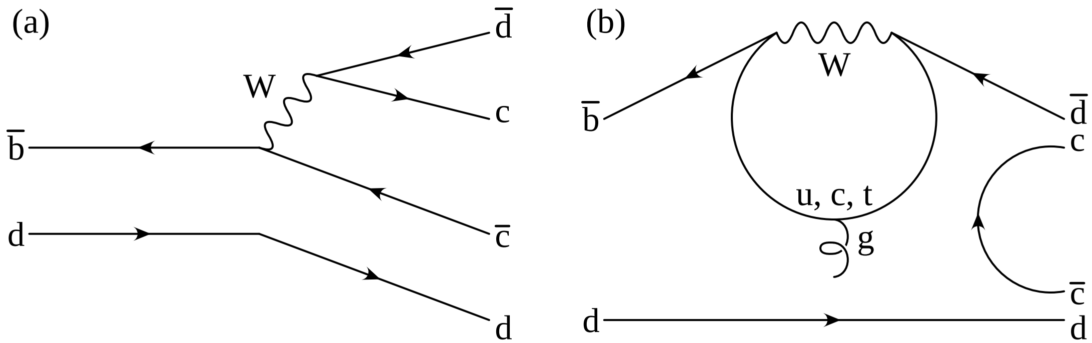

$A_1$: tree $\sim V_{ub}^* V_{ud}$; $A_2$: penguin $\sim V_{tb}^* V_{td}$. If had $A_2 = 0$, indirect CP asymmetry would probe $2\,\arg(V_{tb}^* V_{td} V_{ub}^* V_{ud}) = -2(\beta + \gamma) \sim 2\alpha$. Unfortunately, $A_2 \neq 0$, i.e. penguins are important. Thus, $a_{indir}$ does **not** probe $\alpha$ cleanly.

But: $B_d^0 \to \pi^+\pi^-$ related by isospin to $B^+ \to \pi^+\pi^0$ and $B_d^0 \to \pi^0\pi^0$. Measure $\Gamma(B_d^0(t) \to \pi^+\pi^-)$ and BR's for other 2 decays (and CP-conjugates) $\Longrightarrow$ have enough information to remove "penguin pollution" and obtain $\alpha$.

Experiment: at present, all measured except individual $B^0 \to \pi^0\pi^0$ and $\bar{B}^0 \to \pi^0\pi^0$ rates.

$\gamma$: Many methods proposed. Some (e.g. $B \to DK$) have little theoretical error; others require theoretical input. I will describe one of the second class of methods. (Will come back to it when discussing measurement of new-physics parameters.) (A. Datta, DL, PLB584, 81, 2004)

$B_d^0(t) \to D^+D^-$:
a $\bar{b} \to \bar{c}c\bar{d}$ decay.

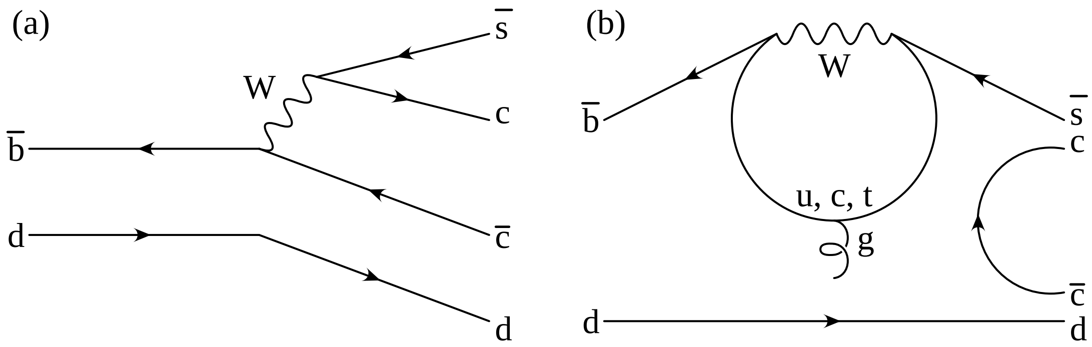



Amplitude has penguin pollution:
use CKM unitarity: tree $\sim V_{cb}^* V_{cd}$ (real), penguin $\sim V_{ub}^* V_{ud} \sim e^{i\gamma}$:

$$A \sim T e^{i\delta_T} + P e^{i\gamma} e^{i\delta_P} \ .$$

Count: there are 5 theoretical parameters: $T$, $P$, $\delta \equiv \delta_T - \delta_P$, and two weak phases ($\beta$ and $\gamma$). But there are only 3 observables $\Longrightarrow$ even if $\beta$ taken from $B_d^0(t) \to J/\psi K_s$, need to add some theoretical input.

This comes from $B_d^0 \to D_s^+ D^-$: a $\bar{b} \to \bar{c} c \bar{s}$ decay:




$$A^{D_s} = T' \, V_{cb}^* V_{cs} + P' \, V_{ub}^* V_{us} \approx T' e^{i\delta'_T} \ .$$

Assumption [flavour SU(3)]: $\lambda T'/T = 1$.

Point: measurement of rate for $B_d^0 \to D_s^+ D^-$ gives us $T'$. The above assumption gives us $T$. We then have 3 unknowns and 3 experimental measurements $\Longrightarrow$ we can get $\gamma$.

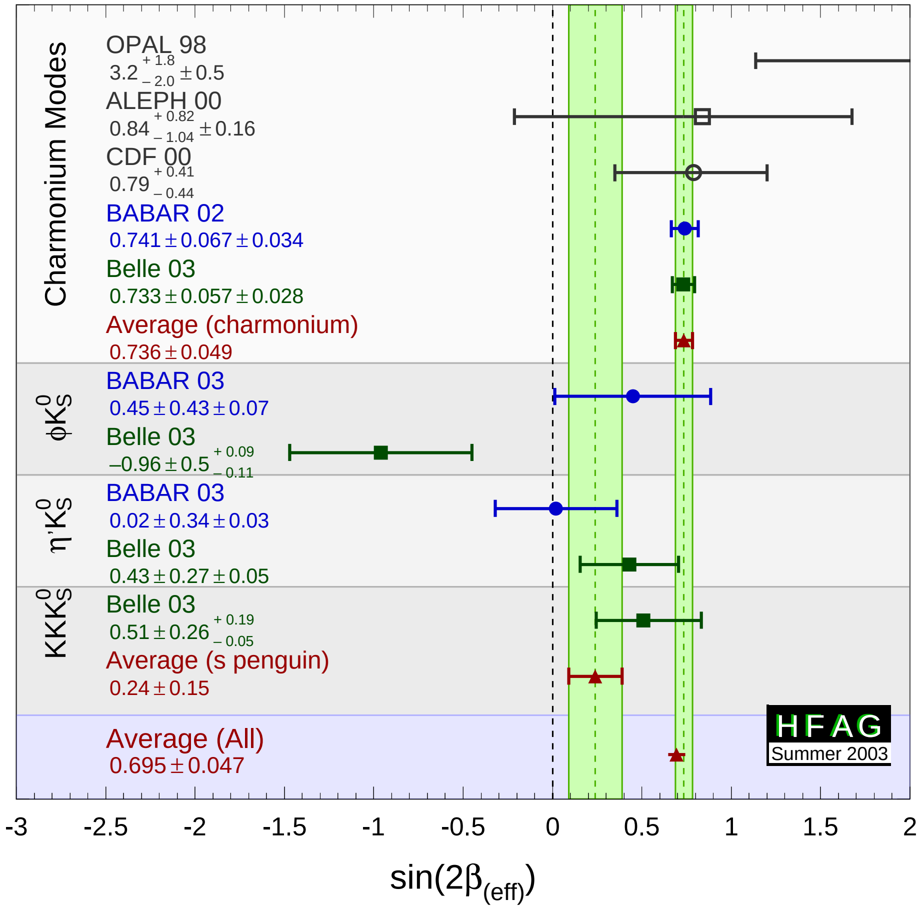
Theoretical error: main SU(3)-breaking effect is $f_{D_s}/f_D = 1.22 \pm 0.04$ (lattice). Remaining error due to second-order effects; estimated to be $\sim 10\%$.

Note: method being used by BaBar to get $\gamma$. This summer?

# New Physics Signals

Point: test SM explanation of CP violation. Discrepancies $\Longrightarrow$ new physics. What are signals of NP?

1. Compare 2 modes which in the SM measure the same CP phase. E.g. $\beta$ is measured in $B_d^0(t) \to J/\psi K_S$. But $\beta$ can also be extracted from pure $b \to s$ penguin decays such as $B_d^0(t) \to \phi K_S$.




$\phi K_S$: Belle finds $\sin 2\beta = -1$. Also, $\sin 2\beta$ extracted from all $b \to s$ penguin decays is $3.1\sigma$ below that from charmonium decays. Hint of new physics?

http://www.slac.stanford.edu/xorg/hfag/

2. $\exists$ many ways to measure CP phases, often with some theoretical input. If the values of the CP phases in these modes disagree at a level beyond the theoretical error, this $\Longrightarrow$ NP.

3. There are some signals which are zero (or small) in the SM.

E.g. phase of $B_s^0$–$\bar{B}_s^0$ mixing is $2\arg(V_{tb}^* V_{ts}) \simeq 0$. Measure CPV in $B_s^0(t) \to J/\psi\eta$. If find large signal, this $\Longrightarrow$ NP.

E.g. study $B \to V_1 V_2$ decays. Measure $\vec{\varepsilon}_1^{\,*T} \times \vec{\varepsilon}_2^{\,*T} \cdot \hat{p}$ (CP-violating triple-product correlations). In SM, all TP's expected to vanish or be very small $\Longrightarrow$ excellent place to search for new physics.
(A. Datta, DL, hep-ph/0303159)

BaBar sees a TP signal in $B \to \phi K^*$ at $1.7\sigma$. Hint of new physics?
(Jim Smith talk, http://moriond.in2p3.fr/QCD/2004/TuesdayMorning/Smith.pdf)

E.g. Inclusive $\mathcal{A}_{CP}^{dir}(b \to s\gamma) \simeq 0$ in SM.
(E.g. T. Hurth, E. Lunghi and W. Porod, hep-ph/0310282)

Many other examples.

4. $B \to K\pi$ decays: Can write amplitudes in terms of diagrams ($T$, $P$, etc.). Some diagrams are expected to be negligible (theoretical input), in which case we have $R_c = R_n$, with

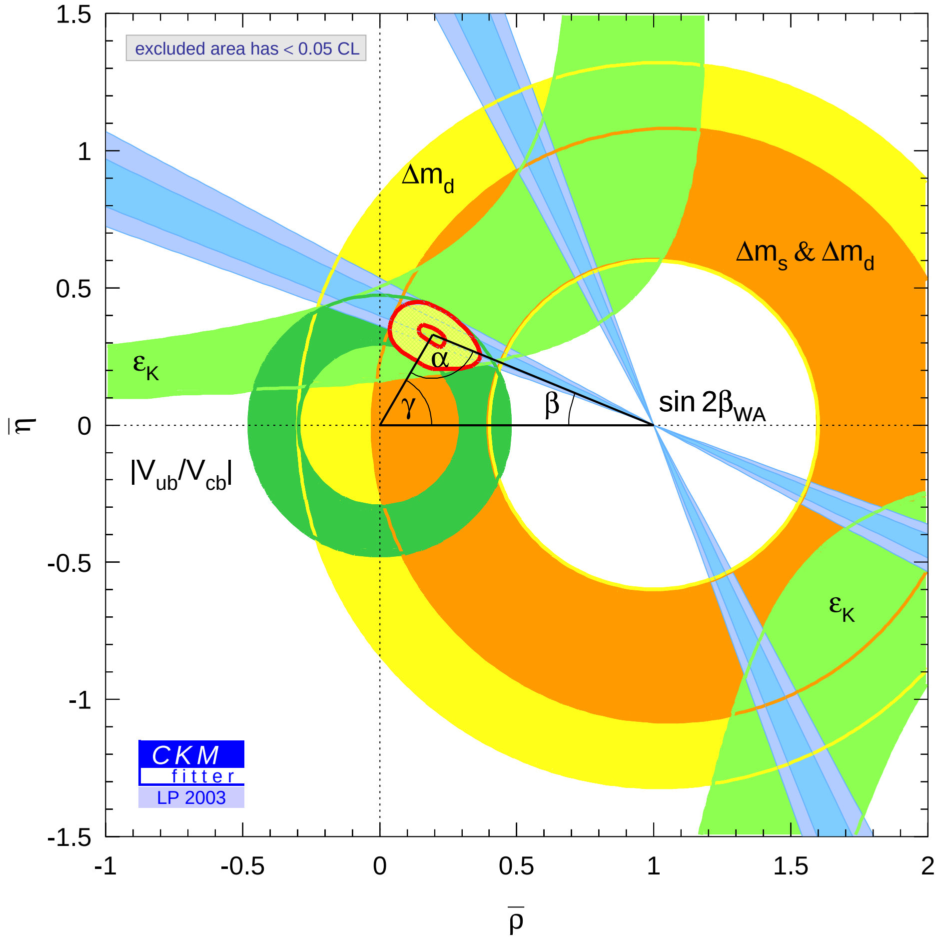
$$R_c \equiv \frac{2\bar{\Gamma}(B^+ \to K^+\pi^0)}{\bar{\Gamma}(B^+ \to K^0\pi^+)} \ , \quad R_n \equiv \frac{\bar{\Gamma}(B_d^0 \to K^+\pi^-)}{2\bar{\Gamma}(B_d^0 \to K^0\pi^0)} \ .$$

Present data:

$$R_c = 1.42 \pm 0.18 \ , \quad R_n = 0.89 \pm 0.13 \ .$$

There is a discrepancy of $2.4\sigma \Longrightarrow$ hint of new physics?

5. One can search for NP by looking for an inconsistency between the measurements of the sides and angles of the unitarity triangle. Independent measurements in the kaon, $B_d^0$ and $B_s^0$ systems currently imply the following constraints (at 95% c.l.):




Note: measurement of $\beta$ agrees with that predicted by independent measurements. These predict: $78^\circ \leq \alpha \leq 118^\circ$, $38^\circ \leq \gamma \leq 79^\circ$ (including hadronic uncertainties). Should either of these CP phases be found to be outside these ranges, this would imply the presence of NP.

http://www.slac.stanford.edu/xorg/ckmfi tter/

There are therefore MANY ways of looking for NP.

# Measuring New-Physics Parameters

Having confirmed the presence of NP, we will want to identify it. Will we have to wait for LHC? Not necessarily: NP parameters can be **measured** through CP violation in $B$ decays. (A. Datta, DL, hep-ph/0404130)

NP principally affects loop-level processes. In general, if NP is present in $B_d^0$–$\bar{B}_d^0$ ($B_s^0$–$\bar{B}_s^0$) mixing, it will also affect $b \to d$ ($b \to s$) penguins. Assume that NP is present only in $b \to s$ transitions (consistent with hints). Assume also that NP operators are roughly the same size as the SM penguin operators.

The NP affects $b \to s$ penguin transitions. There are 20 possible NP $\bar{s}\Gamma_i b\, \bar{q}\Gamma_j q$ operators ($\Gamma_{i,j}$ represent Lorentz structures, colour indices are suppressed). In general, there can be new weak phases and strong phases associated with each operator. A priori, we don't know which operators are present (model-dependent).

Strong phases: generated by rescattering. E.g. in SM, have $(b \to s\bar{c}c) \to (b \to s\bar{s}s)$. However, note: whereas the tree operator has Wilson coefficient $\sim 1$, the largest rescattered penguin operator has W.C. $\sim 0.05$. That is, the rescattered amplitude is $\sim 5\%$ as large as the amplitude causing the rescattering.

NP strong phases come from rescattering from NP operators. But NP operators are only about as big as SM penguins. Rescattered NP operators are only $\sim 5\%$ as large. Reasonable approximation: neglect all NP rescattering, i.e. NP strong phases.

Leads to a great simplification. Use $a_1 e^{i\phi_1} + a_2 e^{i\phi_2} + ... = \mathcal{A} e^{i\Phi}$. That is, for a given $b \to s\bar{q}q$ process ($q = u, d, s, c$), the effects of the NP operators $\bar{s}\Gamma_i b\, \bar{q}\Gamma_j q$ can be parametrized in terms of a single effective NP amplitude $\mathcal{A}^{qq}_{NP}$ and the corresponding weak phase $\Phi_{qq}$.

Point: these NP parameters can be **measured**. Their knowledge will allow us to rule out many NP models, giving us a partial identification before LHC.

Consider $B_d^0(t) \to \phi K_S$ ($b \to s\bar{s}s$ penguin). In the presence of NP, its amplitude can be written

$$A' = P'_{SM} e^{i\delta'_P} + \mathcal{A}^{ss}_{NP} e^{i\Phi_{ss}} ~.$$

Count: assuming that the phase of $B_d^0$–$\bar{B}_d^0$ mixing ($\beta$) is known independently, there are 4 theoretical parameters: $P'_{SM}$, $\mathcal{A}^{ss}_{NP}$, $\delta'_P$ and $\Phi_{ss}$. But there are only 3 observables $\Longrightarrow$ need to add some theoretical input.

This comes from $B_s^0(t) \to \phi K_S$. This is a $b \to d\bar{s}s$ penguin, and has no NP contributions. Its amplitude is

$$A = P_u e^{i\gamma} e^{i\delta_u} + P_{SM} e^{i\delta_P} ~.$$

Here too there are 3 observables. Assuming that $\gamma$ is known from independent non-$b \to s$ measurements, can extract $P_{SM}$, $P_u$ and $\delta \equiv \delta_u - \delta_P$. Use SU(3) relation $\lambda P'_{SM}/P_{SM} = 1$ to provide necessary theoretical input $\Longrightarrow$ measure $\mathcal{A}^{ss}_{NP}$ and $\Phi_{ss}$.

Can obtain all $\mathcal{A}_{NP}^{qq}$ and $\Phi_{qq}$ ($q = u, d, s, c$) similarly. (There are other methods as well.) Will allow us to distinguish among possible NP models.

Some models conserve isospin. (e.g. gluonic penguins with an enhanced chromomagnetic moment). This implies that $\mathcal{A}_{NP}^{uu} = \mathcal{A}_{NP}^{dd}$.

Some models predict that the NP phase $\Phi_{qq}$ is universal (e.g. $Z$-mediated FCNC's).

In general, the values of $\mathcal{A}_{NP}^{qq}$ and $\Phi_{qq}$ found are process-dependent. However, some models predict that NP contributions to certain $b \to s\bar{q}q$ decays are process-independent (e.g. SUSY with R-parity breaking).

All of these predictions can be tested (and possibly excluded).

Bottom line: knowledge of $\mathcal{A}_{NP}^{qq}$ and $\Phi_{qq}$ will allow a partial identification of the new physics, before its direct discovery at LHC.

# Conclusions

Raison d'être of $B$ physics is to find physics beyond the SM.

There are **many** signals of new physics in measurements of CP violation in $B$ decays.

Given a NP signal, it is even possible to **measure** NP parameters. This will allow a partial identification, before direct measurements at future high-energy colliders.